Arizona Department of Environmental Quality

Douglas A. Ducey
Governor

Misael Cabrera
Director

via e-mail

August 12, 2019
FPU20-028

Ms. Catherine Jerrard
AFCEC/CIBW
706 Hangar Road
Rome, NY 13441

RE: WAFB - ST012 – Praxis Environmental Technologies, Inc. sulfate distribution model inquiry – Request for field correlation to modeled expectations, and discussion by stakeholders

Dear Ms. Jerrard:

Arizona Department of Environmental Quality (ADEQ) Federal Projects Unit (FPU) and ADEQ contractor UXO Pro, Inc., are respectfully requesting insight to sulfate field measurement results compared to modeled dispersion. ADEQ presumes that sulfate injection and monitoring have provided a volume of field data usable for correlating to model predictions.

Mr. Lloyd "Bo" Stewart, with Praxis Environmental Technologies, Inc. (Praxis) has performed independent modeling exercises with regard to sulfate dispersion. The Praxis-originated model reveals sulfate distribution which differs from other models presented for ST012. Praxis is attempting to correlate the Praxis model to existing field data, and to open discussion on predictive model refinements.

The purpose of the Praxis modeling is to provide order-of-magnitude matches to observed sulfate arrival at extraction wells and values for field-scale dispersivity. If a disparity exists between the actual field results and the Praxis model results, then discussion can be framed on influence factors and process lines to refine future models.

Discussion points can include, but not be limited to:

1. Should "lower" dispersion values be used when numerically modeling sulfate distribution calculations?

2. Can actual extraction rates and durations be incorporated into the ongoing numeric model? Actual extraction rates realized likely differ substantially from design rates and are expected to significantly impact the sulfate distribution.

3. Can investigation be conducted into the disparities between predicted and field-measured, extraction well sulfate concentrations (i.e., assume much lower sulfate, leading to question "where is the sulfate?")?

Attached to this cover letter is an *Interim Sulfate Distribution Estimates*, a Praxis document dated June 17, 2019. The document presents site condition understanding, Praxis's model construction, and Praxis's predictive results. Please feel free to forward to stakeholders for reading and feedback discussion.

Closure

Thank you for the opportunity to request information. Should you have any questions regarding this correspondence, please contact me by phone at (602) 771-4121 or e-mail miller.wayne@azdeq.gov.

Sincerely,

Wayne Miller

Wayne Miller
ADEQ Project Manager, Federal Projects Unit
Remedial Projects Section, Waste Programs Division

cc:

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ADEQ Reading and Project File	

INTERIM SULFATE DISTRIBUTION ESTIMATES

Enhanced Bioremediation at ST012

Date: June 17, 2019

Prepared By: Lloyd "Bo" Stewart, PhD, PE
Praxis Environmental Technologies, Inc., Burlingame, CA

OUTLINE

PREAMBLE

This memorandum is intended to frame discussion on data collected during the initial field implementation of sulfate reduction and the relation to input parameters for subsequent numerical modeling of sulfate distribution. The purpose of the modeling is to provide order-of-magnitude matches to observed sulfate arrival at extraction wells and values for field-scale dispersivity. The modeling yields approximate results and accuracy is not implied by the number of significant digits presented.

1. Conceptual Site Model Summary

A comprehensive conceptual site model (CSM) including the UWBZ, LPZ and LSZ is presented in Appendix A of the TEE Pilot Test Evaluation Report (BEM, 2011). The geologic materials in the saturated zone are subdivided into five main hydrostratigraphic units described from the bottom upwards (BEM, 2003):

- The Aquitard, occurring at approximately 260 ft to 245 ft bgs;
- The LSZ extending from approximately 245 ft to 210 ft bgs;
- The LPZ, extending from approximately 210 ft to 195 ft bgs;
- The UWBZ, extending from approximately 195 to 160 ft bgs; and
- The Cobble Zone, extending from approximately 160 ft to 145 ft.

Lithologic descriptions of the zones can be found in Table A.3.3.1.1 1 (BEM, 2011). In January 2010 the water table at Site ST012 was approximately 158 ft bgs and rising at an average rate of 3.4 ft per year. The horizontal gradient of both the LSZ and UWBZ averaged 0.005 feet per foot (ft/ft) toward the east.

The site hydrogeologic properties for the present modeling are summarized in Table 1. The estimated velocity and direction of ambient groundwater flow through each zone is listed. The effective aquifer porosity (ϕ=0.25) is assumed the same for all zones.

For the sulfate distribution evaluation, the target EBR soil volumes are illustrated in Figures 1 through 3 for the CZ, UWBZ and LSZ.

Table 1. Groundwater Flow Properties for Modeling Sulfate Injection

Aquifer Zone	Thickness Z ft	Hydraulic Conductivity ft/day	Ambient GW Velocity U ft/day	Ambient GW Direction
CZ	15	70	0.343	
UWBZ	35	12.7	0.0654	+4^0 due E
LPZ	15	-	-	-
LSZ	35	16	0.101	+16^0 due E

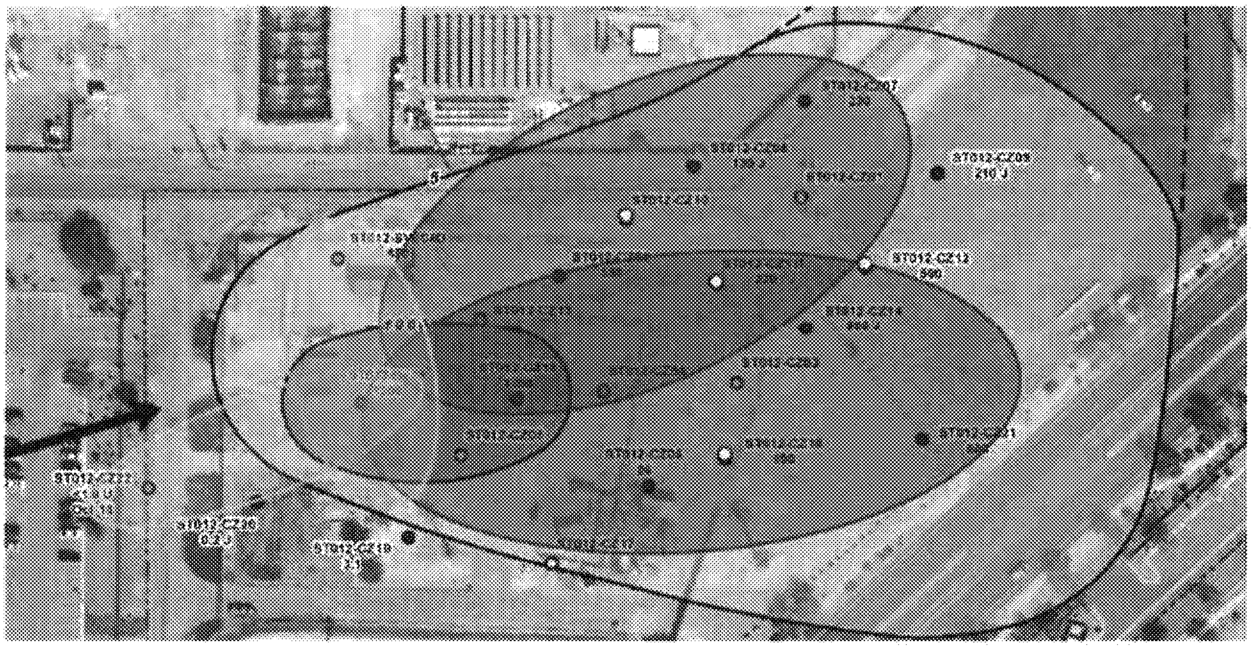

Figure 1. Conceptual Model for pre-EBR Benzene Plume in the CZ (FVM #7 Figure 3-2)

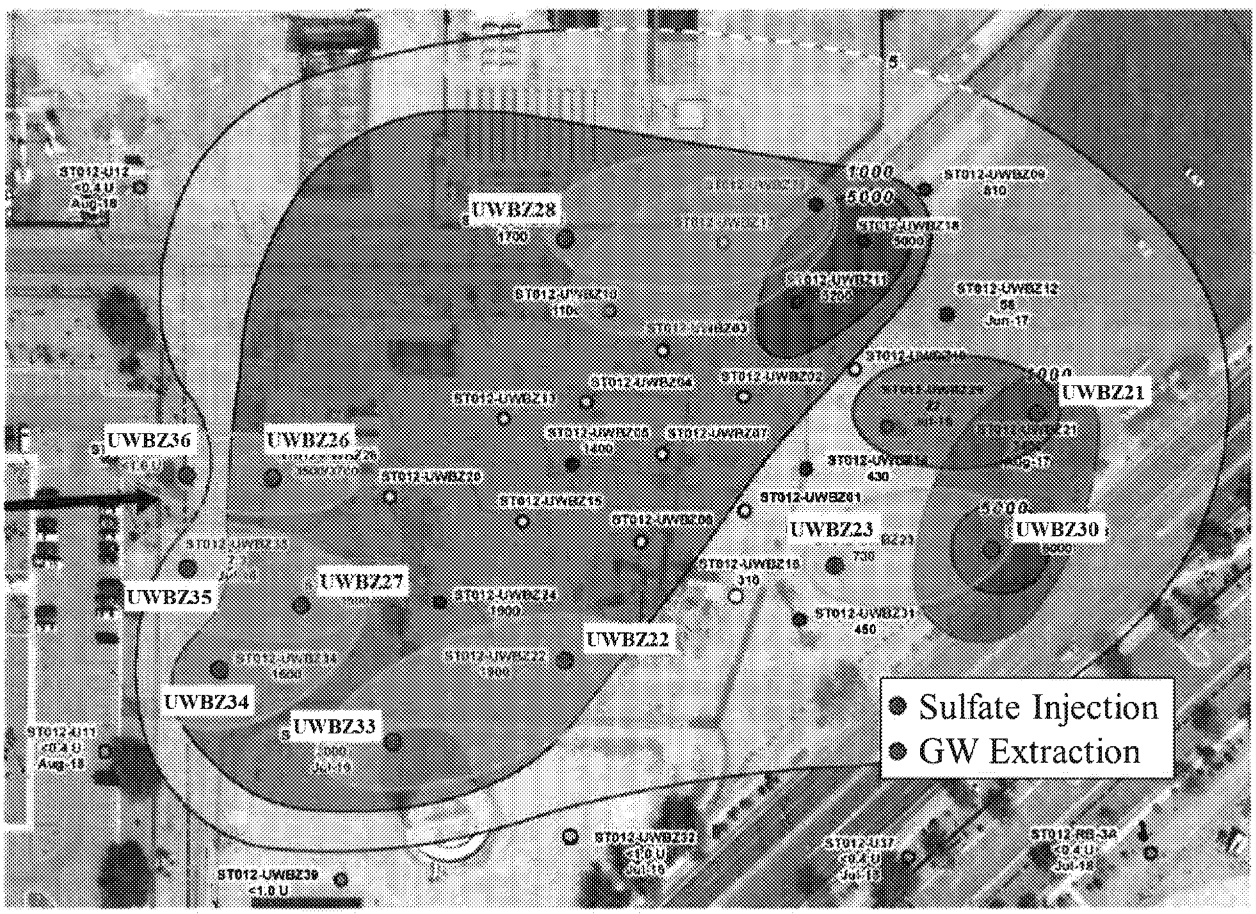

Figure 2. Conceptual Model for pre-EBR Benzene Plume in the UWBZ (FVM #7 Figure 3-3)

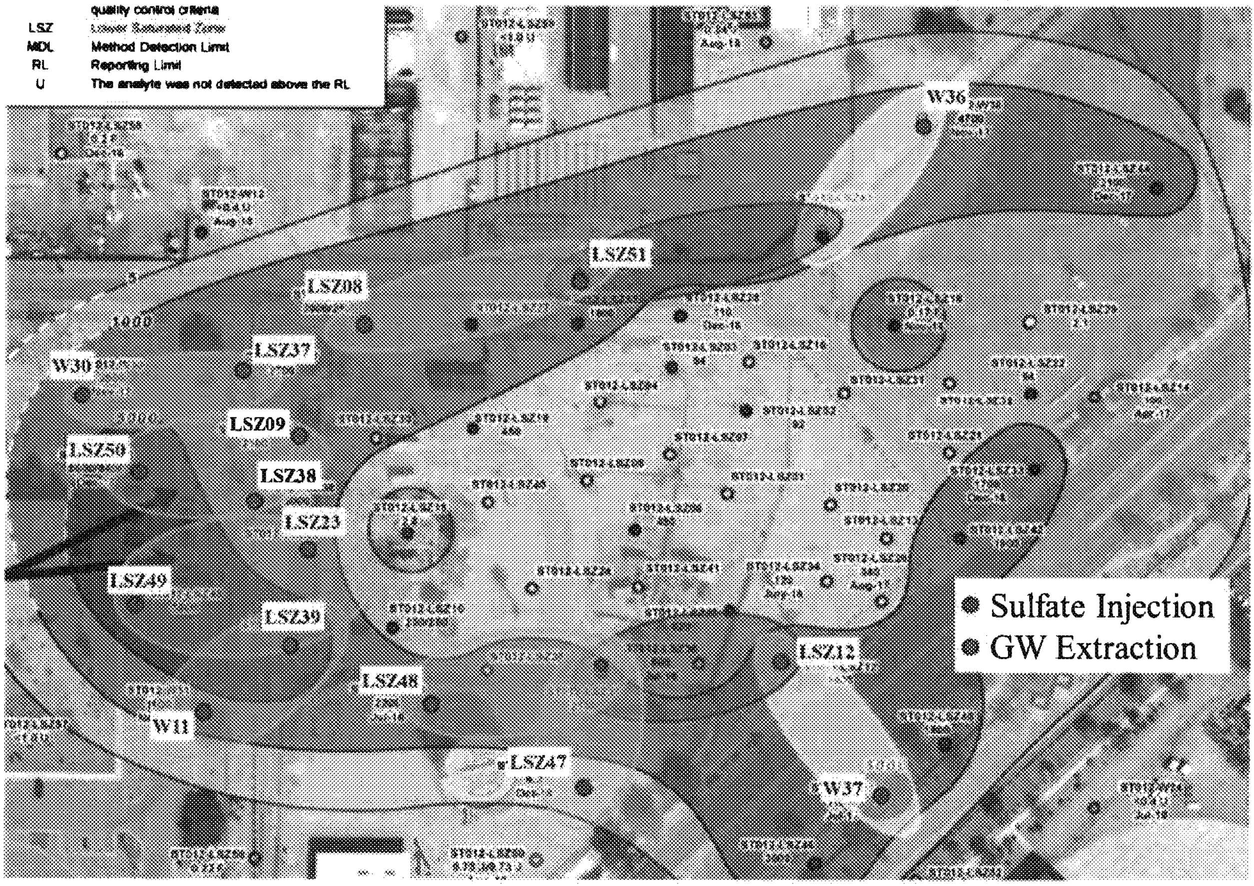

Figure 3. Conceptual Model for pre-EBR Benzene Plume in the LSZ (FVM #7 Figure 3-4)

2. Sulfate Injection Data (through May 6, 2019)

Data for sulfate injection through May 6, 2019 is listed in Table 2 below. The second column provides the volume of water injected into the subsurface on the data listed in column one. The first row at the top lists the wells for injection, the second row lists the planned tons of sodium sulfate for injection per well as described in Field Variance Memorandum #7. The third row shows the estimated actual tons injected through May 6, 2019. These estimates are based on bi-weekly summaries provided by email and Monthly BCT meeting slides. For modeling purposes, the injection is assumed to be continuous rather than periodic. In this manner, the total injected water and sulfate volumes are divided by the number of days between the start and finish to provide average injection rates. In general, the water injection rate exceeds the ambient groundwater velocity and is much less than the total groundwater extraction rate such that the averaging approach provides a good approximation to the pulsed injection.

Groundwater extraction rates from individual wells were roughly estimated from the plots of cumulative extraction volume for each individual well in each zone. These plots were provided monthly in the BCT meeting slides. The current plots of cumulative extraction volumes for the UWBZ and LSZ are shown in Figures 4 and 5, respectively.

Table 2. Sodium Sulfate Mass (Tons) and Water Volume Injection per Well

		Well:	UWBZ33	UWBZ36	UWBZ34	UWBZ35	W11	LSZ08	LSZ47	LSZ48	LSZ49	SVE04D	CZ22
Date	Injection	Tons Plan:	29	6	13	15	10	16	6.5	7.5	7.5	3	3
	(gal)	Tons Actual:	29	6	14.52	15	9.86	16.22	8.4	7.52	7.61	0	0.87
11/12/2018	10000		6										
12/4/2018	10000		4										
1/9/2018	5000		2										
1/10/2019	5000		2										
1/16/2019	5000		2.5										
1/17/2019	5000		2.5										
1/24/2019	5000		2										
1/25/2019	5000		2										
1/29/2019	5000			2									
2/5/2019	7500		3										
2/6/2019	7500		3										
2/18/2019	2500			1									
2/19/2019	2500			1									
2/27/2019	5000			2									
2/28/2019	10000				4								
3/5/2019	9500				2.32		1.68						
3/6/2019	6000				1		1						
3/12/2019	5000				1.1		0.9						
3/14/2019	5000				1		1						
3/15/2019	5000				0.84		1.16						
3/19/2019	5000				0.84		1.16						
3/20/2019	7000				1.8		1.2						
3/21/2019	5000				1.62		0.38						
3/27/2019	7200					1.62	1.38						
3/28/2019	7500					3							
3/29/2019	7400					3							
4/8/2019	5000					3							
4/9/2019	6000					1		2					
4/10/2019	5700					0.68		1.32					
4/11/2019	9900					2.7		2.3					
4/17/2019	6100							3					
4/18/2019	9800							5					
4/25/2019	6000							2.6	0.4				
4/26/2019	6000								3				
4/29/2019	9800								5				
4/30/2019	9800									5			
5/1/2019	12000									2.52	3.48		
5/2/2019					UWBZ27 off		LSZ39 off						
5/3/2019	4000										2		
5/6/2019	6000										2.13		0.87

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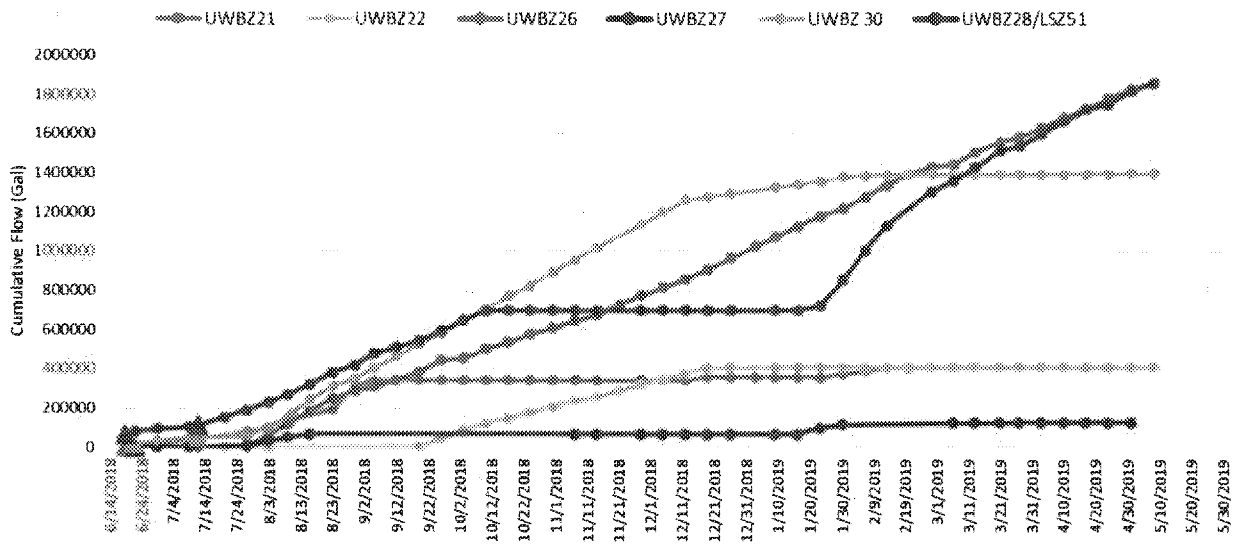


Figure 4. UWBZ Cumulative Extraction Volume

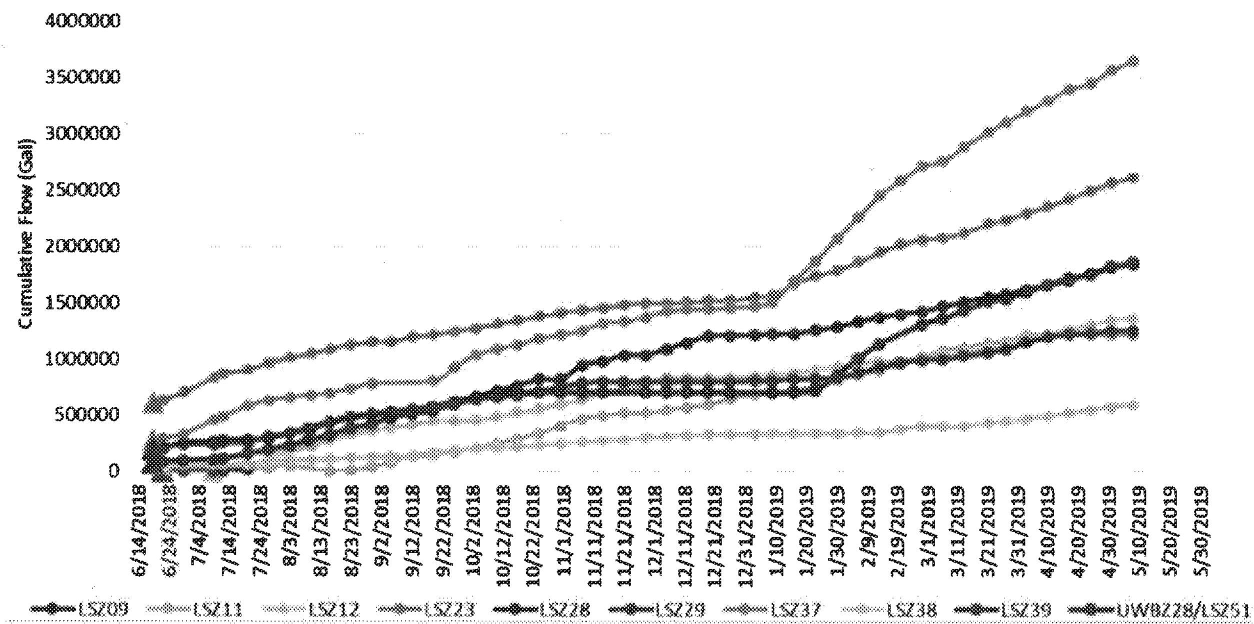


Figure 5. LSZ Cumulative Extraction Volume

The extraction from UWBZ28/LSZ51 is assumed to be evenly split between the two zones; although the UWBZ would be expected to yield a lesser volume than the LSZ. These figures illustrate large deviations from the planned extraction rates provided in Appendix F of the Final Pilot Study Implementation Work Plan (April 2018). The rates are generally lower than planned. For modeling injected sulfate movement from an individual well, the extraction rate from individual wells was averaged over the duration of sulfate injection and roughly the month following cessation.

The available field screening data for sulfate concentrations in extraction wells is provided in Table 3. These data are copied from the May 2019 BCT Meeting slides. Theses concentrations will be used to assess the transport of sulfate using the models described in the next section.

Table 3. Sulfate Field Screening Results

Injection Points	Extraction Well	Date	Sulfate (mg/L)
UWBZ33	UWBZ22 (average pre injection laboratory sulfate = 11 mg/L)	12/17/2018	30
		12/21/2018	45
		12/26/2018	146
		1/15/2019	45
		1/18/2019	40
		1/21/2019	38
		1/24/2019	41
		1/25/2019	250
		1/28/2019	10
		1/29/2019	35
		1/31/2019	89
		2/1/2019	57
		2/5/2019	37
		2/11/2019	37
		2/15/2019	36
		2/18/2019	40
		2/22/2019	pump down
		2/25/2019	pump down
		3/1/2019	pump down
		3/4/2019	pump down
		3/8/2019	pump down
LSZ47	LSZ11	5/1/2019	630

Injection Points	Extraction Well	Date	Sulfate (mg/L)
UWBZ33 UWBZ34	UWBZ27 (average pre injection laboratory sulfate = 108 mg/L)	12/17/2018	15
		12/21/2018	30
		12/26/2018	>150
		1/15/2019	71
		1/18/2019	57
		1/21/2019	66
		1/24/2019	48
		1/25/2019	50
		2/11/2019	54
		2/15/2019	48
		3/1/2019	94
		3/4/2019	112
		3/15/2019	119
		3/20/2019	97
		3/29/2019	350
		4/8/2019	297
		4/16/2019	520
		4/23/2019	1140
		4/26/2019	570
		5/1/2019	1110
W11	LSZ39 (average pre injection sulfate = 132 mg/L)	3/29/2019	850
		4/9/2019	153
		4/16/2019	210
		4/23/2019	1220
		4/26/2019	1230
		5/1/2019	1180

Injection Points	Extraction Well	Date	Sulfate (mg/L)
UWBZ36	UWBZ26 (average pre-injection sulfate = 3.6 mg/L)	1/31/2019	22
		2/1/2019	9
		2/6/2019	25
		2/11/2019	10
		2/15/2019	12
		2/18/2019	16
		2/22/2019	22
		2/25/2019	38
		3/1/2019	66
		3/4/2019	67
		3/8/2019	104
		3/15/2019	101
		3/29/2019	99
		4/9/2019	81
		4/16/2019	150
LSZ08	LSZ37	4/23/2019	20
		4/26/2019	70
		5/1/2019	77
	LSZ51	4/23/2019	6
		4/26/2019	18
		5/1/2019	12

3. Modeling Approach

The first step in modeling the sulfate injection and subsequent migration utilizes a simple potential flow model to approximate groundwater movement induced by sources, sinks, and regional flow in a uniform aquifer of constant thickness (e.g., LSZ, UWBZ, and CZ are modeled independently). For this calculation, the computer program RESSQ was employed. The program can calculate two-dimensional contaminant transport by advection and adsorption (no dispersion or diffusion) in a homogeneous, isotropic confined aquifer of uniform thickness when regional flow, sources, and sinks create a steady state flow field. RESSQ calculates the streamline pattern in the aquifer and the location of contaminant fronts around sources at various times. RESSQ was developed at the Lawrence Berkeley Laboratory based on a solution procedure used by Gringarten and Sauty [1975a, b]. A user's guide for the program and a listing of the code are given in the reference provided in Appendix A of this document.

The RESSQ model was used to calculate streamlines and arrival times for injected sulfate at ST012 assuming no dispersion. Initial calculations of streamlines under the approximated conditions for sulfate injection suggested curvilinear pathlines of sulfate particles were sufficiently linear a short distance from injection wells to allow dispersion to be approximated by 1D linear flow. This condition exists as a result of the relatively low ambient groundwater velocities and low average injection rates as compared to extraction rates. Hence, a well-known solution (shown below in Figure 6) for modeling tracer injection and estimating longitudinal dispersivity was employed to match observed sulfate concentrations at extraction wells.

Semi-infinite system with third-type source boundary condition

Governing equation

One-dimensional solute-transport equation:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x} - \lambda C \qquad (63)$$

Boundary conditions:

$$VC_o = VC + D\frac{\partial C}{\partial x}, \qquad x = 0 \qquad (64)$$

$$C, \frac{\partial C}{\partial x} = 0, \qquad x = \infty \qquad (65)$$

Initial condition:

$$C = 0, \qquad 0 < x < \infty \qquad \text{at } t = 0 \qquad (66)$$

Assumptions:

1. Fluid is of constant density and viscosity.
2. Solute may be subject to first-order chemical transformation (for a conservative solute, $\lambda = 0$).
3. Flow is in x-direction only, and velocity is constant.
4. The longitudinal dispersion coefficient (D), which is equivalent to D_x (eq. 7), is constant.

Analytical solution

The following equation is modified from Cleary and Ungs (1978, p. 10):

where

$$U = \sqrt{V^2 + 4\lambda D}.$$

For a conservative solute ($\lambda = 0$), the solution to equation 68 is given by Lindstrom and others (1967) and van Genuchten and Alves (1982, p. 10) as

$$\boxed{C(x,t) = C_o\left\{\frac{1}{2}\operatorname{erfc}\left[\frac{x - Vt}{2\sqrt{Dt}}\right] + \sqrt{\frac{V^2 t}{\pi D}}\exp\left[-\frac{(x - Vt)^2}{4Dt}\right] - \frac{1}{2}\left[1 + \frac{Vx}{D} + \frac{V^2 t}{D}\right]\exp\left(\frac{Vx}{D}\right)\operatorname{erfc}\left[\frac{x + Vt}{2\sqrt{Dt}}\right]\right\}. \qquad (68)}$$

Cleary, R.W., and Ungs, M.J., 1978, Analytical models for groundwater pollution and hydrology: Princeton University, Water Resources Program Report 78-WR-15, 165 p.

Figure 6. One-Dimensional, Linear Solution for Sulfate Transport including Dispersion

4. Subphase 1 Sulfate Injections in UWBZ

A summary of input data for modeling sulfate injection and dispersion in the UWBZ is provided in Tables 4 and 5. The average injection rate and extraction rates for injection in individual wells were input to RESSQ to generate approximate steady state streamlines for the event and the arrival time of the initial sulfate front, assuming the sulfate is not subjected to dispersion. The row labeled "PLAN" in Table 5 repeats the design extraction rates provided in Appendix F of the Pilot Test Work Plan. The actual values fall short of the design rates and will result in the sulfate distribution being significantly different from the distribution presented in the Pilot Test Work Plan.

Table 4. UWBZ Sulfate Injection Subphase 1

Injection Well	Sulfate Plan tons	Sulfate Actual tons	Water Volume gallons	Start Date	End Date	Duration days	Average Rate gpm
UWBZ33	29	29	65,000	11/12/18	2/6/19	86	0.53
UWBZ36	6	6	15,000	1/29/19	2/27/19	30	0.36
UWBZ34	13	14.5	35,700	2/28/19	3/21/19	22	1.2
UWBZ35	15	15	33,100	3/27/19	4/11/19	16	1.5
UWBZ23	6	TBD	TBD	TBD	TBD	TBD	TBD

Table 5. UWBZ Model Extraction Rates

Injection Well	UWBZ21 gpm	UWBZ22 gpm	UWBZ26 gpm	UWBZ27 gpm	UWBZ28 gpm	UWBZ30 gpm	UWBZ Total gpm
PLAN	4.4	5.2	5.1	5.0	4.8	4.3	28.6
UWBZ33	0.4	0.9	4.9	0.3	2.1	2.3	10.9
UWBZ36	0.4	0.0	4.7	0.1	4.0	0.2	9.4
UWBZ34	0.1	0.0	4.2	0.1	3.0	0.1	7.5
UWBZ35	0	0	4.5	0.1	2.6	0	7.2
UWBZ23	TBD	TBD	TBD	TBD	TBD	TBD	TBD

The estimated streamlines during and after injection at UWBZ33 are illustrated in Figure 7. Each streamtube represents approximately 0.18 gallon per minute (gpm) assuming a thickness of 35 feet. Hence, the average injection rate of 0.53 gpm in UWBZ33 yields three streamlines and these are colored red in Figure 7. Under the assumed flow conditions, undispersed sulfate would be completely captured by UWBZ22 but would not arrive for nearly a year (~November 2019). This figure illustrates the relatively linear shape of the streamlines over the majority of the distance traveled allowing the assumption of linear flow to assess dispersion. This figure also illustrates an approximate capture zone for ambient flow through the site.

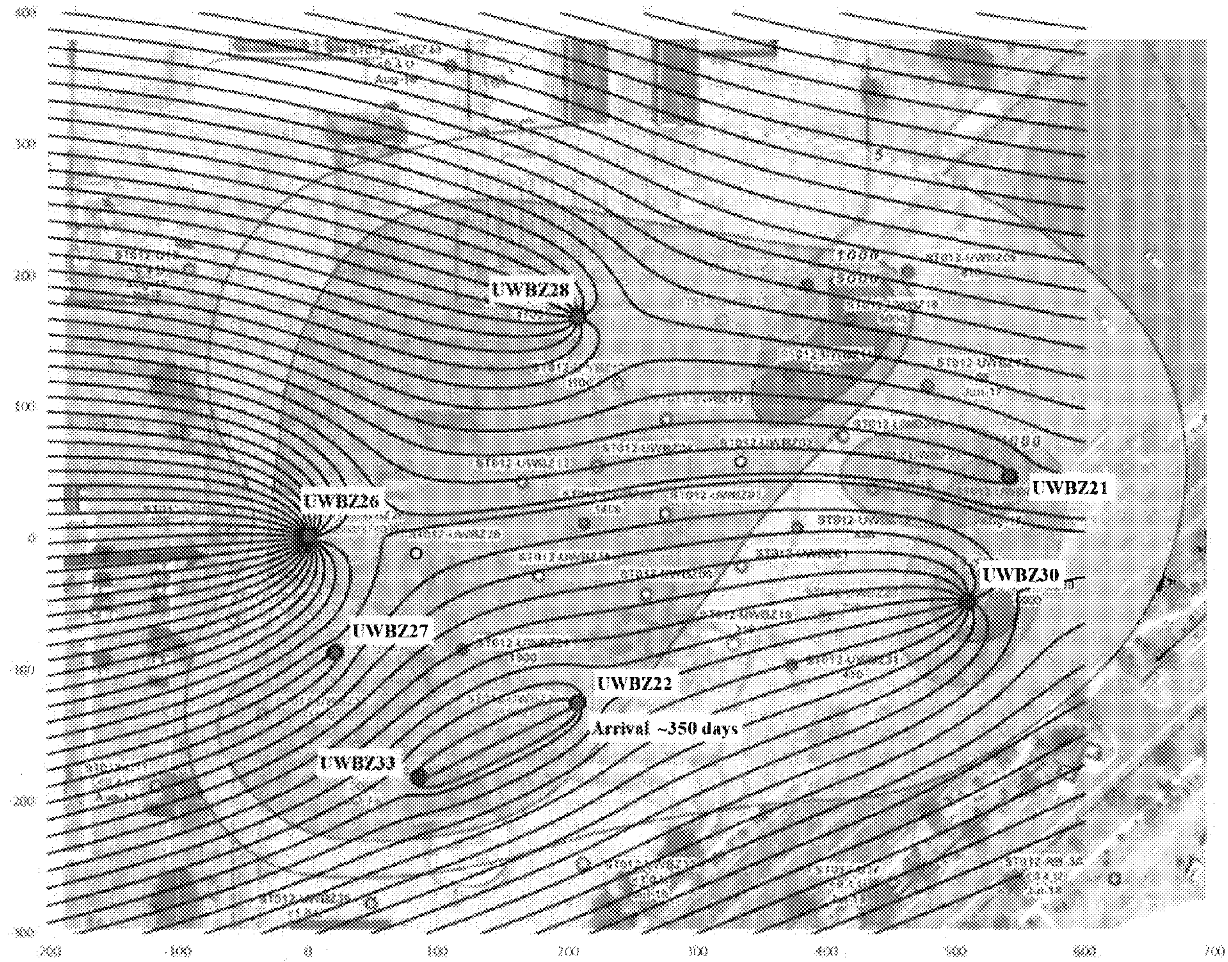


Figure 7. Approximate Streamlines during Sulfate Injection in UWBZ33

The transport solution described in Figure 6 was employed to estimate the longitudinal dispersion of sulfate after injection. The velocity (V) in this equation was estimated to be the arrival time of streamlines at UWBZ22 divided the distance between UWBZ33 and UWBZ22. This velocity compared well with the average of velocities calculated by RESSQ along the pathlines. The dispersion coefficient (D) was calculated as the product of the average velocity (V) and a longitudinal dispersivity (α_L) as follows:

$$D = \alpha_L V$$

The numerical modeling results for sulfate distribution provided in the Pilot Test Work Plan assumed a longitudinal dispersivity of 20 feet. In this work a range of values was employed. In addition, the injected sulfate concentration is diluted at the extraction well by the extraction of unimpacted groundwater. This dilution is included in estimating the sulfate concentration in extracted water by calculating the ratio of total extraction to extraction of the sulfate injected water. In the example of UWBZ33, Figure 7 illustrates extraction in UWBZ22 includes three streamlines from UWBZ33 and two from outside suggesting a dilution of 40% (i.e., 60% of the 0.9 gpm includes 0.54 gpm from UWBZ33).

Estimated concentrations of sulfate in extracted water from UWBZ22 over time are illustrated in Figure 8 where longitudinal dispersion and dilution are included. The field screening sulfate concentrations from Table 3 are also plotted with Day 0 equal to 12-Nov-18. Calculations were performed with three different values for dispersivity. Initial results suggest a dispersivity of 20 feet is too high. Note that all three curves meet at the undispersed arrival time of about 350 days. Monitoring of sulfate in UWBZ22 should continue; however, the pump in this well went down around 20-Feb-19 ending the monitoring.

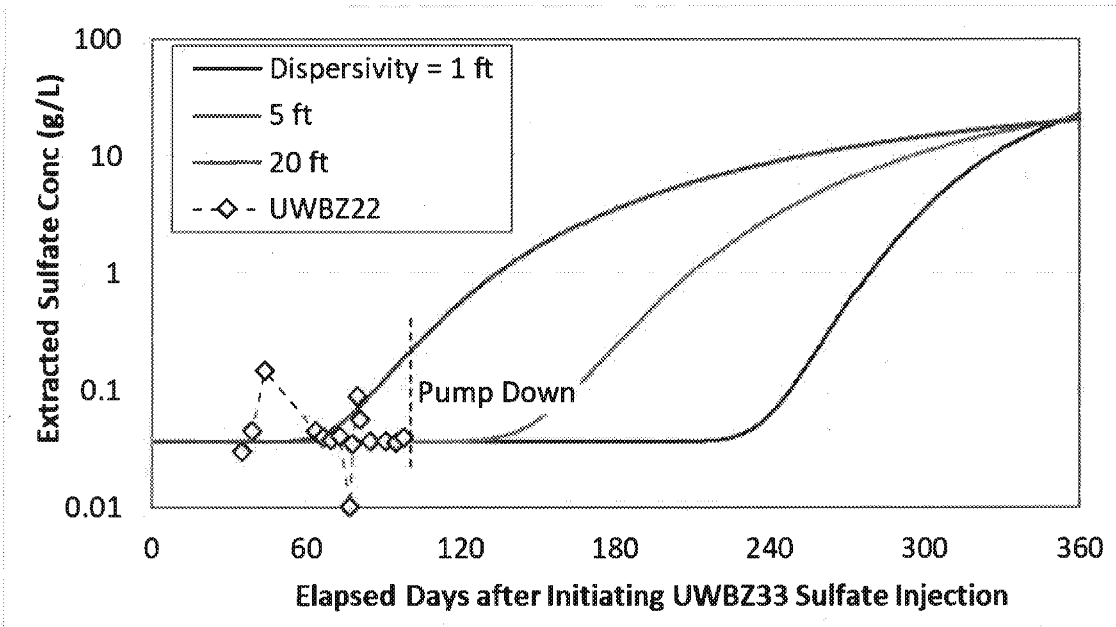


Figure 8. Approximate History of Sulfate Concentration in Extracted Water from UWBZ22

Similar calculations of streamlines, arrival times, dispersion, and extraction well sulfate concentrations were performed for the sulfate injections in UWBZ36 and UWBZ34. Plots similar to Figures 7 and 8 are provided in Appendix B.

The estimated streamlines during and after injection at UWBZ36 are completely captured by UWBZ26 with an undispersed arrival time of about 60 days. Estimated concentrations of sulfate in extracted water from UWBZ26 over time are illustrated in Figure 9. The field screening sulfate concentrations from Table 3 are also plotted with Day 0 equal to 29-Jan-19. Results suggest a dispersivity less than 5 feet is appropriate and that dilution was greater than expected, the entire sulfate plume was not captured, or the tail of the sulfate injection impacted the extracted concentration.

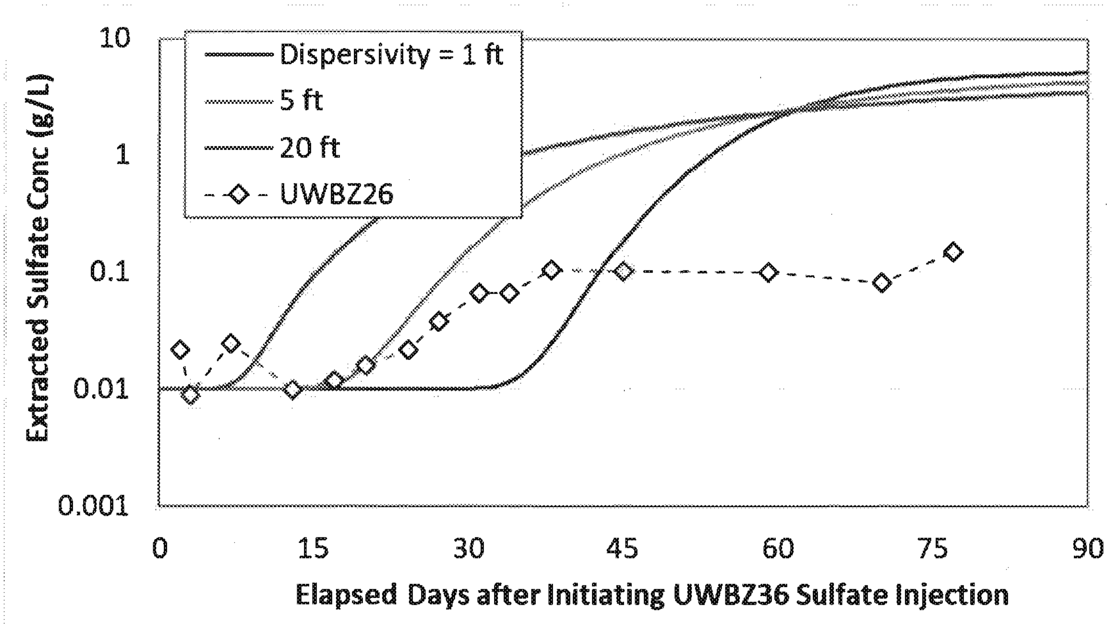


Figure 9. Approximate History of Sulfate Concentration in Extracted Water from UWBZ26

The estimated streamlines during and after injection at UWBZ34 are largely uncaptured by the extraction configuration during injection as shown in Appendix B. Undispersed sulfate is expected to show up at UWBZ27 after 3 or 4 months. Including dispersion the estimated concentrations of sulfate in extracted water from UWBZ27 over time are illustrated in Figure 10 along with the field screening sulfate concentrations with Day 0 equal to 28-Feb-19. Results suggest a dispersivity between 5 and 20 feet is appropriate. The low pumping rate in UWBZ27 suggests the sulfate concentrations would be undiluted from the injection.

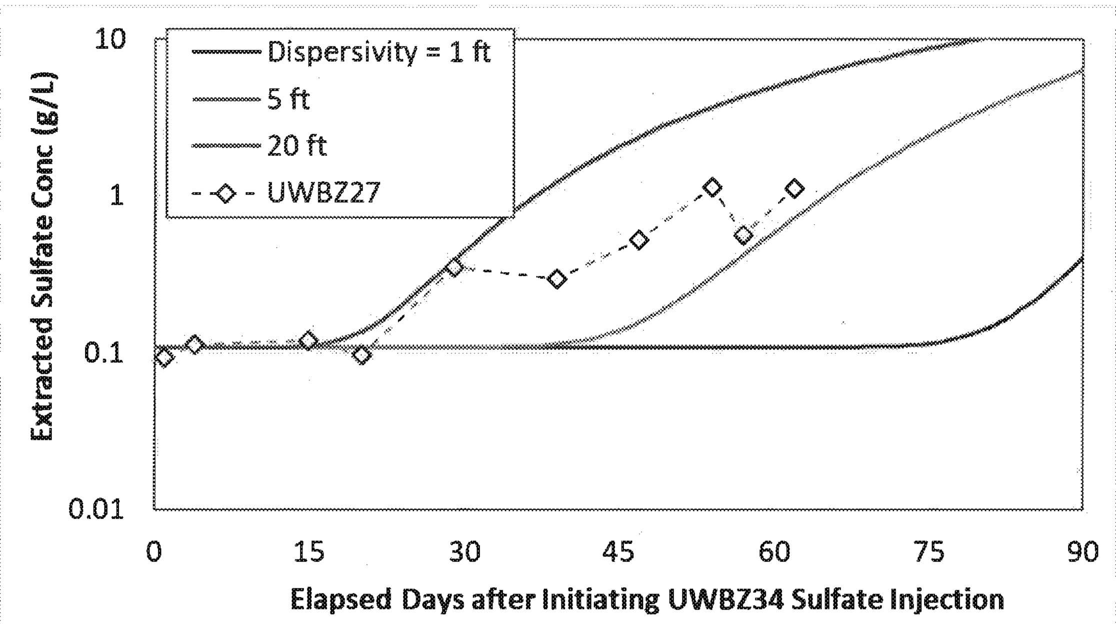


Figure 10. Approximate History of Sulfate Concentration in Extracted Water from UWBZ27

5. Subphase 1 Sulfate Injections in LSZ

A summary of input data for modeling sulfate injection and dispersion in the LSZ is provided in Tables 6 and 7.

Table 6. LSZ Sulfate Injection Subphase 1

Injection Well	Sulfate Plan tons	Sulfate Actual tons	Water Volume gallons	Start Date	End Date	Duration days	Average Rate gpm
W11	10	9.9	24,600	3/5/19	3/27/19	23	0.8
LSZ08	16	16.2	33,500	4/9/19	4/25/19	17	1.5
LSZ47	6.5	8.4	16,700	4/25/19	4/29/19	5	2.9
LSZ48	7.5	7.5	14,800	4/30/19	5/1/19	2	5.2
LSZ49	7.5	7.6	15,200	5/1/19	5/6/19	6	1.8
LSZ50	6.75	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*
W30	3	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*
W36	3	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*
W37	3	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*

Table 7. LSZ Model Extraction Rates

Injection Well	LSZ09 gpm	LSZ11 gpm	LSZ12 gpm	LSZ23 gpm	LSZ37 gpm	LSZ38 gpm	LSZ39 gpm	LSZ51 gpm	LSZ Total gpm
PLAN	4.0	4.0	3.3	3.9	4.6	4.8	4.5	3.8	38.8
W11	4.4	1.8	4.1	6.1	10.0	2.2	3.1	2.9	35
LSZ08	4.5	0.0	3.1	5.8	8.1	2.1	1.2	2.3	27
LSZ47	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*
LSZ48	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*
LSZ49	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*
LSZ50	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*
W30	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*
W36	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*
W37	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*	*TBD*

Deleted Extraction Wells: LSZ28 = 4.8 gpm
LSZ29 = 2.5 gpm

The estimated streamlines during and after injection at W11 are illustrated in Figure 11. Each streamtube represents approximately 0.4 gallon per minute (gpm) assuming a thickness of 35 feet. Under the assumed flow conditions, undispersed sulfate would be completely captured by LSZ39 and would arrive in about 70 days. Figure 11 also illustrates the relatively linear shape of the streamlines over the majority of the distance traveled. This figure also illustrates an approximate capture zone for ambient flow through the site.

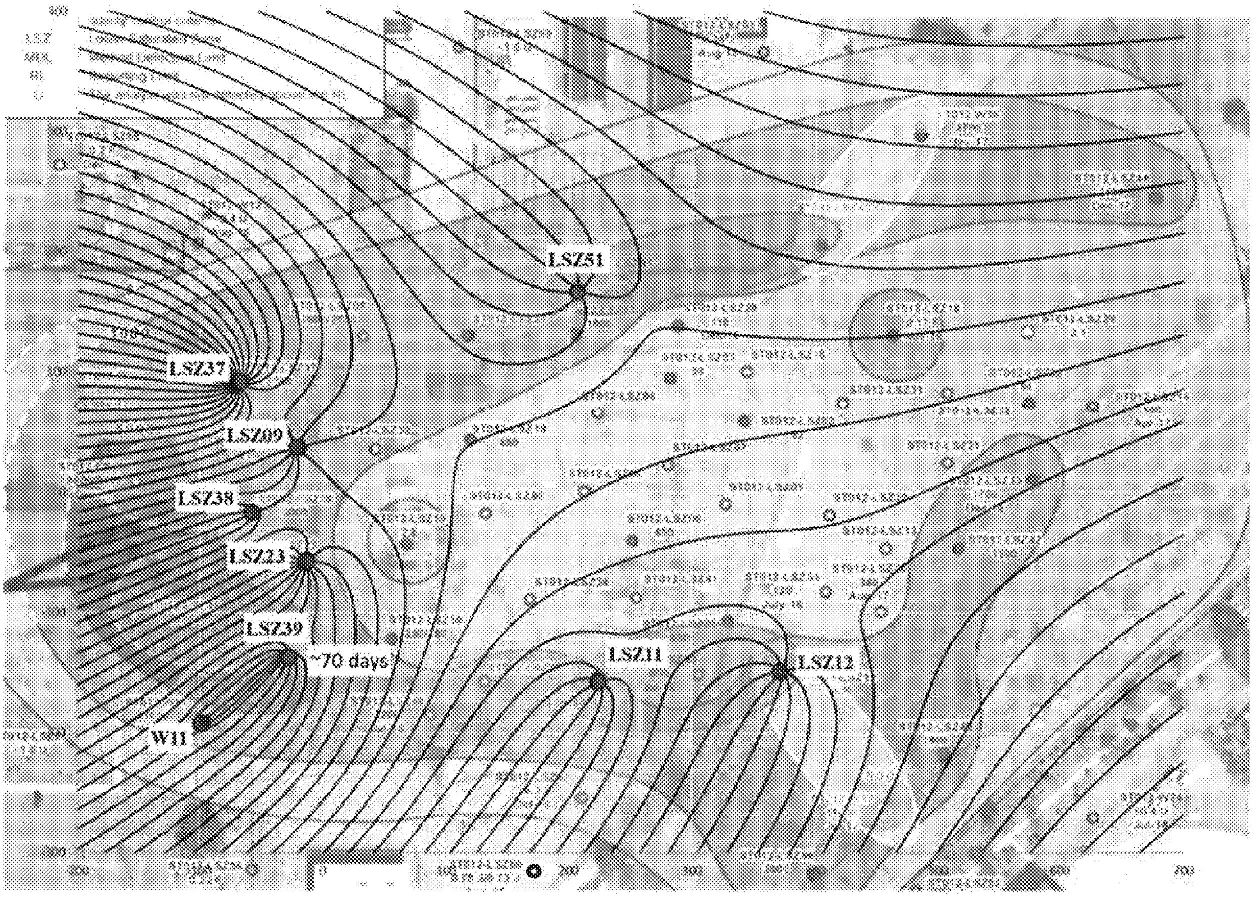


Figure 11. Approximate Streamlines during Sulfate Injection in W11

Estimated concentrations of sulfate in extracted water from LSZ39 over time are illustrated in Figure 12 where longitudinal dispersion and dilution are included. The field screening sulfate concentrations from Table 3 are also plotted with Day 0 equal to 5-Mar-19. Results suggest a dispersivity of 20 feet is too high and a value closer to 1 foot is appropriate. Pumping in LSZ39 ceased on 2-May-19 (Day 58). Additional data will be available from subsequent monitoring of EBR.

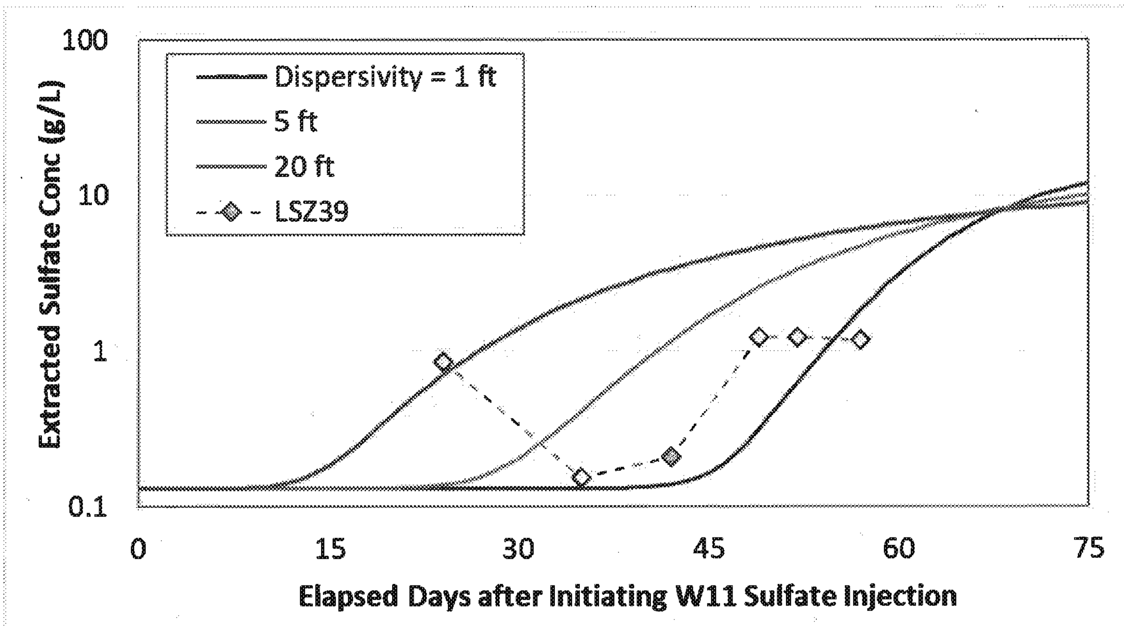


Figure 12. Approximate History of Sulfate Concentration in Extracted Water from LSZ39

Similar calculations of streamlines, arrival times, dispersion, and extraction well sulfate concentrations were performed for the sulfate injections in LSZ08. Under the current extraction configuration, the estimated sulfate pathlines during and after injection at LSZ08 are captured primarily by LSZ09 with an undispersed arrival time of about 180 days as illustrated in Figure 13. The associated streamlines (0.4 gpm) are illustrated in Figure 14.

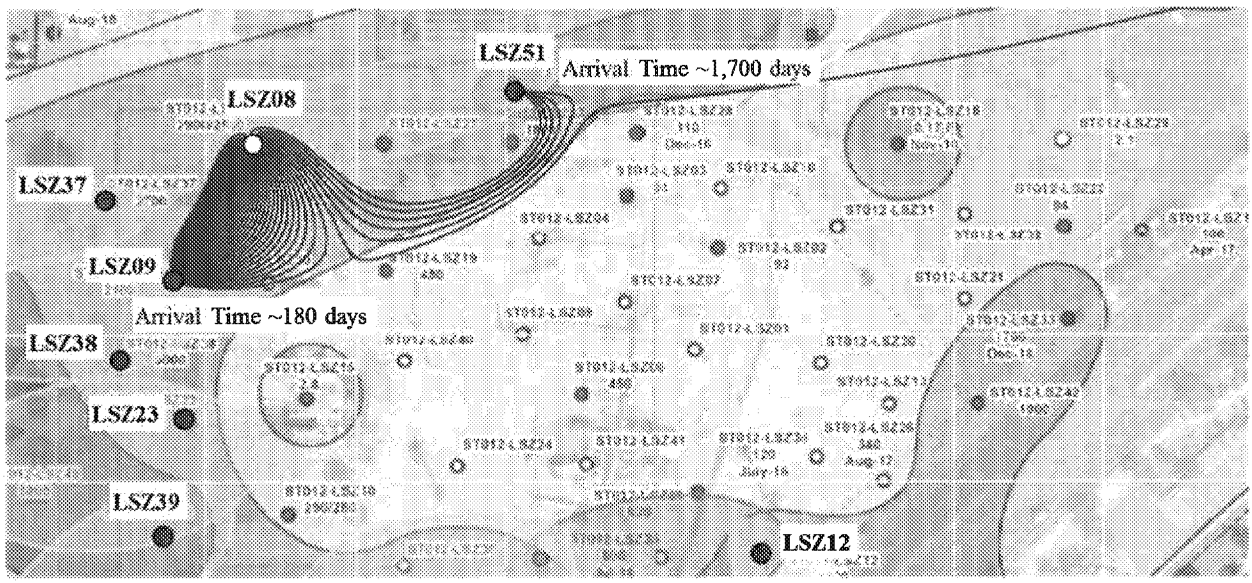


Figure 13. Approximate Sulfate Pathlines during Injection in LSZ08

ED_005025_00010283-00017

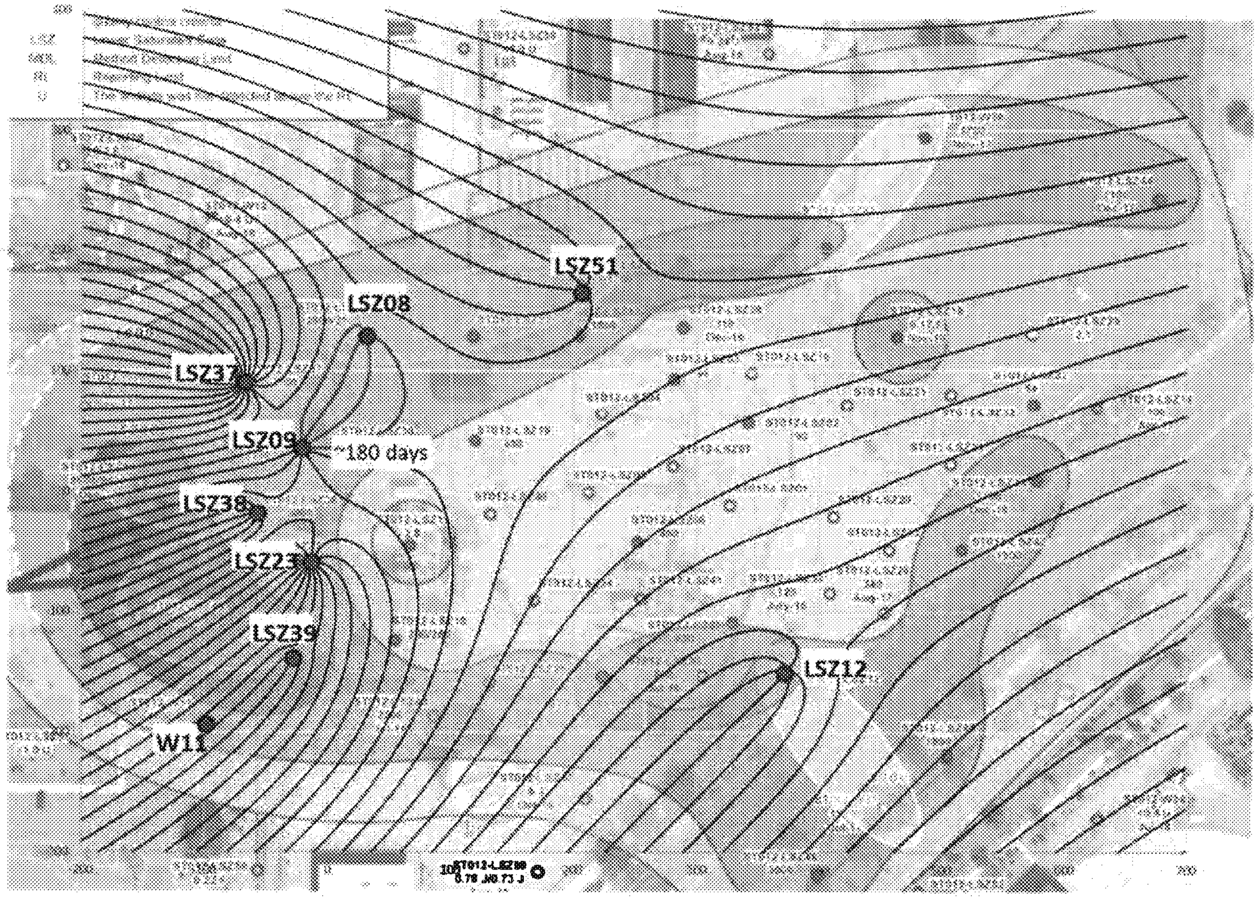


Figure 14. Approximate Streamlines during Sulfate Injection in LSZ08

Estimated concentrations of sulfate in extracted water from LSZ09 over time are illustrated in Figure 15. Currently, no field screening of sulfate concentrations is being performed in LSZ09.

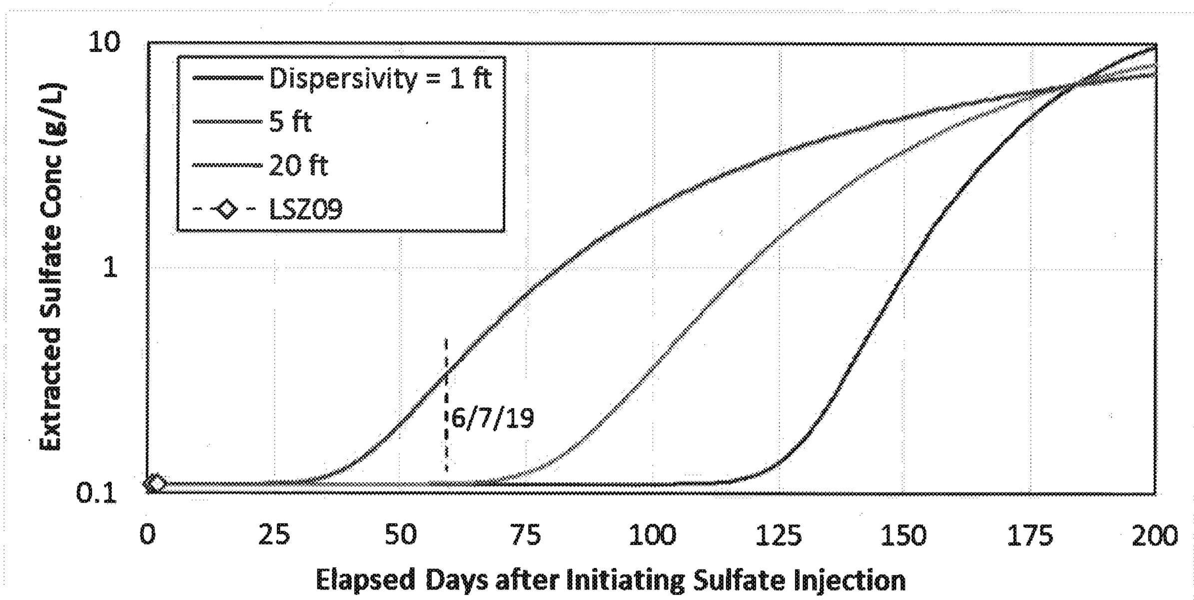


Figure 15. Approximate History of Sulfate Concentration in Extracted Water from LSZ09

6. Interim Recommendations

Based on the modeling and its results compared to early field data, interim recommendations include:

1. Initiate field screening of sulfate concentrations in LSZ09.
2. Future numerical modeling of sulfate distribution should include calculations with lower dispersivities.
3. Future numerical modeling should utilize actual extraction rates and durations; the current extraction rates differ substantially from design rates and are expected to significantly impact the sulfate distribution.
4. Investigate the reasons for the disparity between predicted and much lower field-measured values for the extracted sulfate concentrations after arrival at extraction wells (i.e., where is the sulfate?).

WATER RESOURCES MONOGRAPH SERIES 10

Groundwater Transport:

Handbook of Mathematical Models

Iraj Javandel, Christine Doughty, and Chin-Fu Tsang

Appendix H

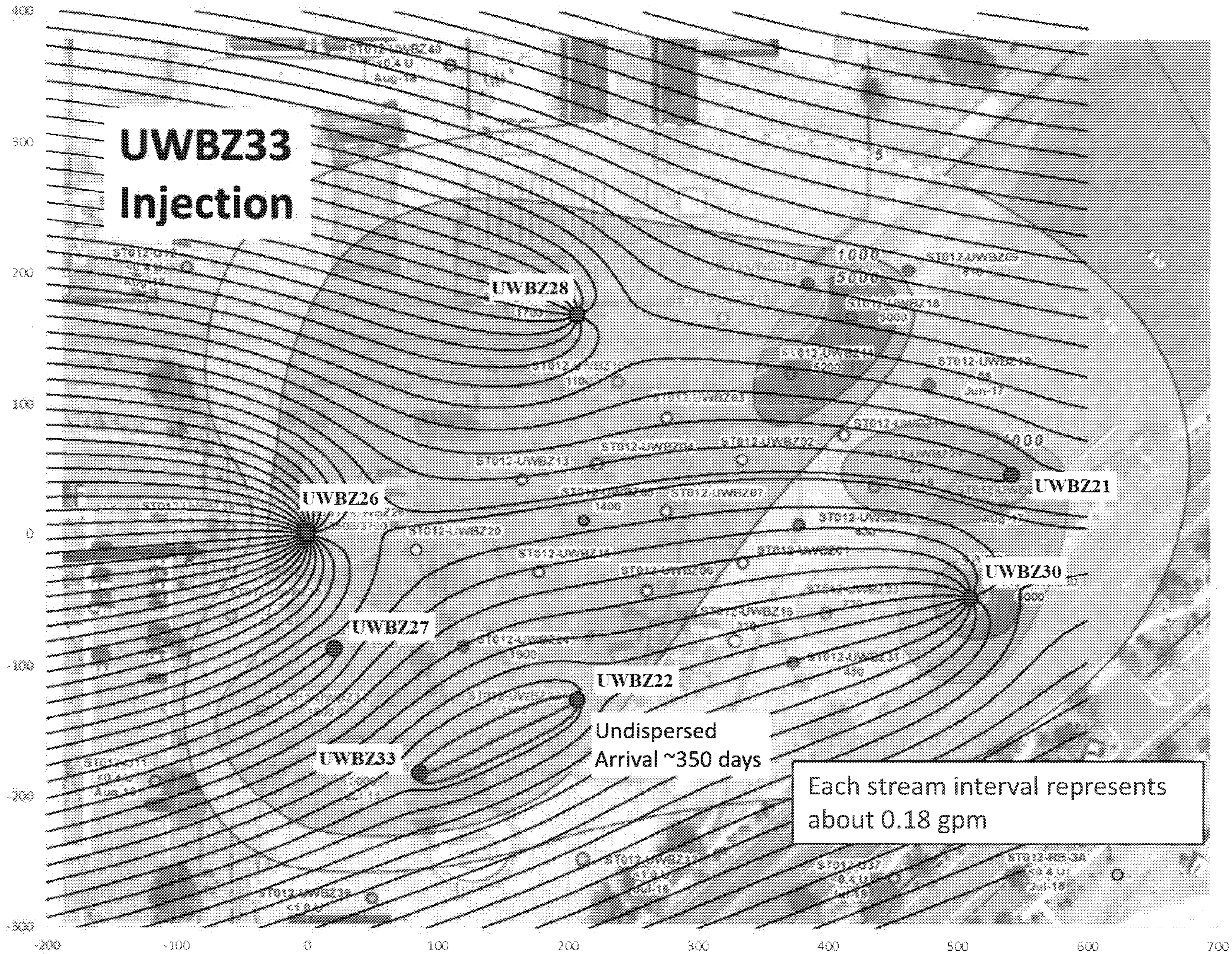
RESSQ: A Computer Program for Semianalytical Contaminant Transport

The computer program RESSQ calculates two-dimensional contaminant transport by advection and adsorption (no dispersion or diffusion) in a homogeneous, isotropic confined aquifer of uniform thickness when regional flow, sources, and sinks create a steady state flow field. Recharge wells and ponds act as sources and pumping wells act as sinks. RESSQ calculates the streamline pattern in the aquifer (subroutine FLOW), the location of contaminant fronts around sources at various times (subroutine FLOW), and the variation of contaminant concentration with time at sinks (subroutine CONCEN). RESSQ was developed at the Lawrence Berkeley Laboratory based on a solution procedure used by *Gringarten and Sauty* [1975a,b]. A user's guide for the program and a listing of the code are given below.

AMERICAN GEOPHYSICAL UNION
WASHINGTON, D.C.
1984

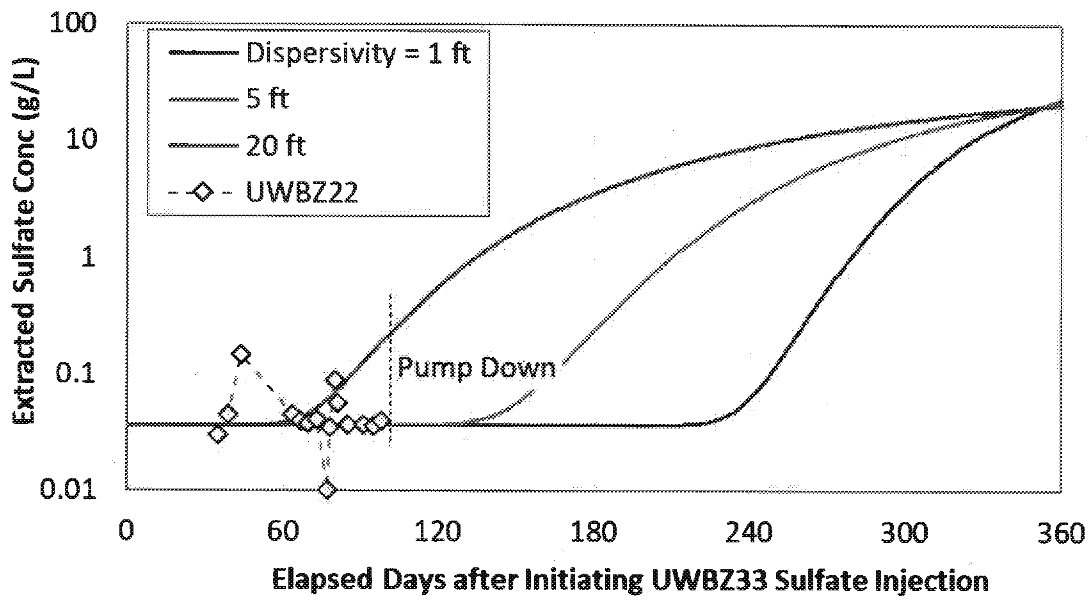
Appendix B
Additional Figures

Sulfate Injection in UWBZ33 is entirely within capture zone of UWBZ22



UWBZ33 Injection

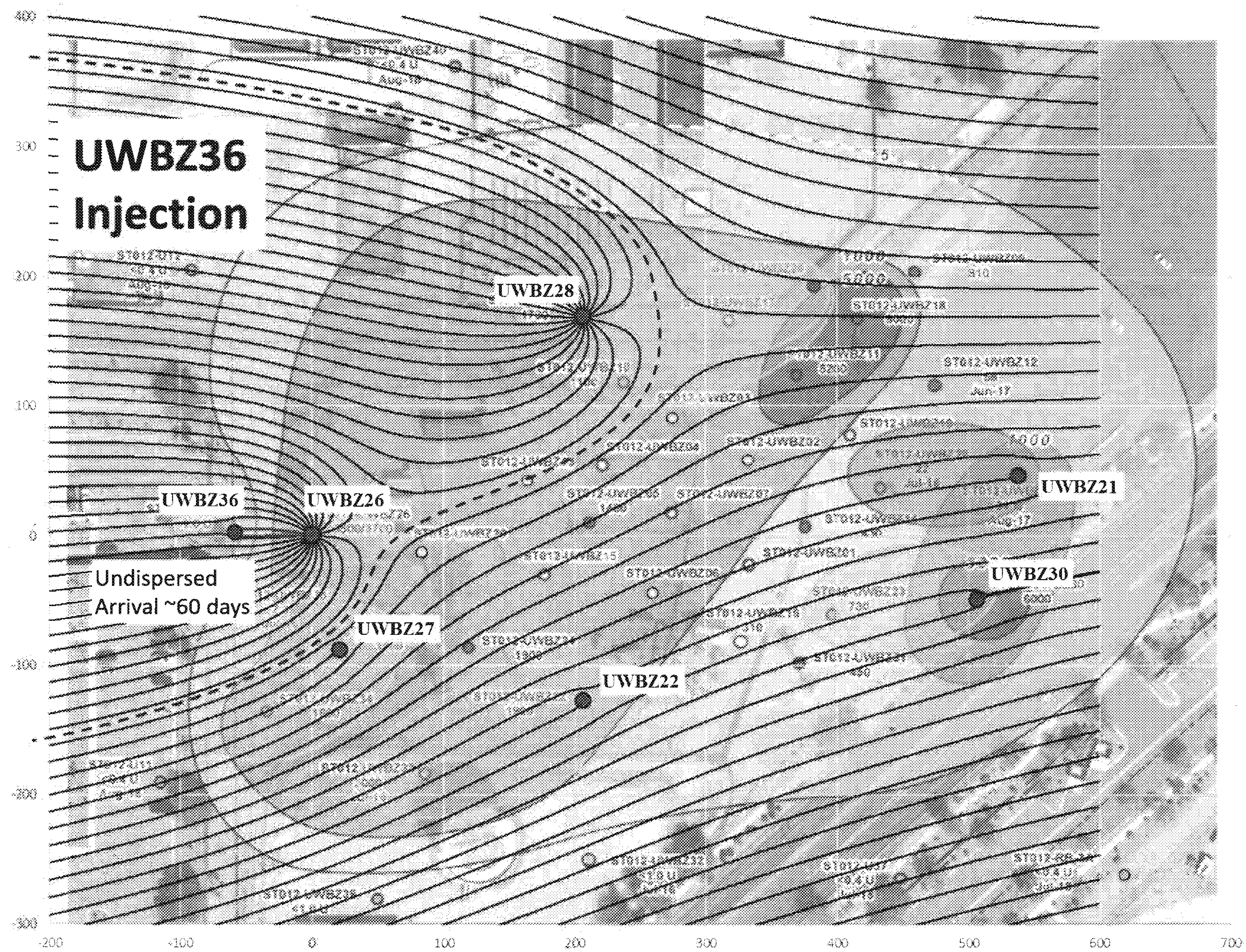
Estimated Extracted Sulfate Concentration in UWBZ22



Sulfate Injection in UWBZ33 Day 0 = 11/12/18

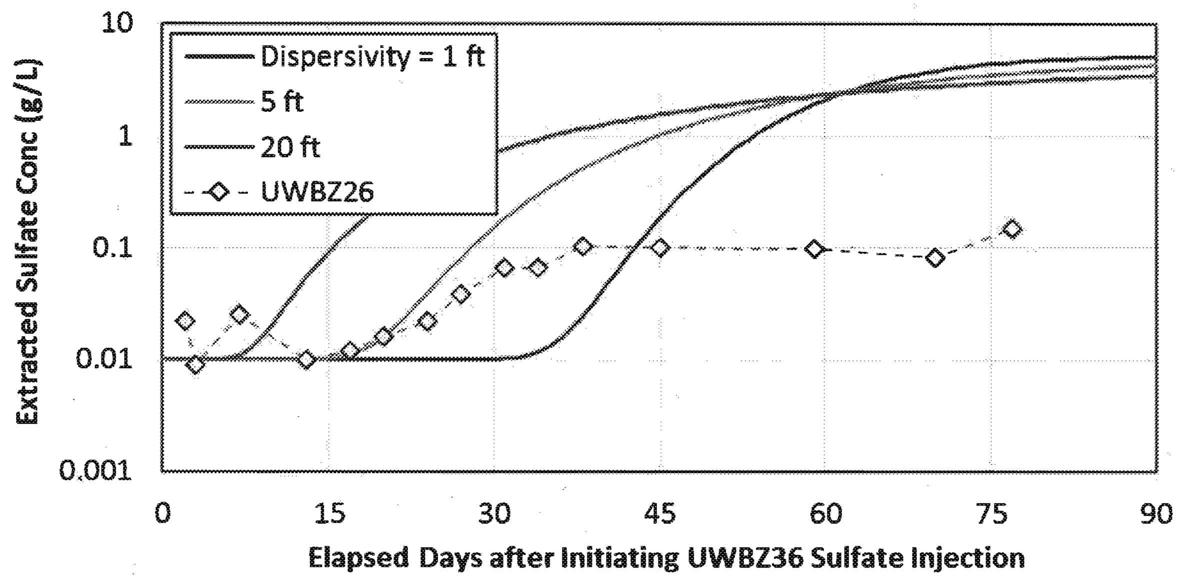
Pumping in UWBZ22 stopped ~2/20/19 (Day 100) so no more sulfate readings

Sulfate Injection in UWBZ36 is entirely within capture zone of UWBZ26



UWBZ36 Injection

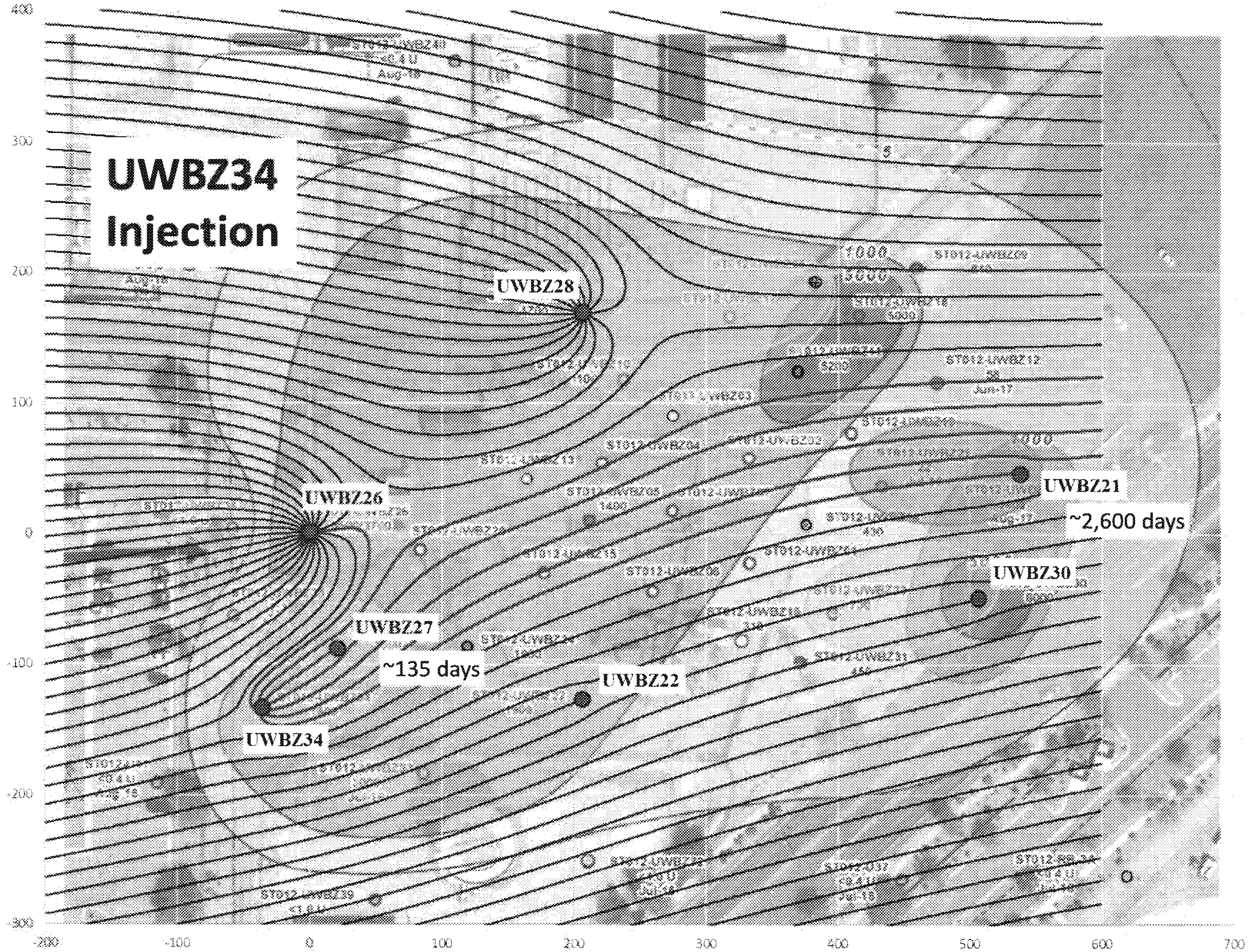
Estimated Extracted Sulfate Concentration in UWBZ26



Sulfate Injection in UWBZ36 Day 0 = 1/29/19

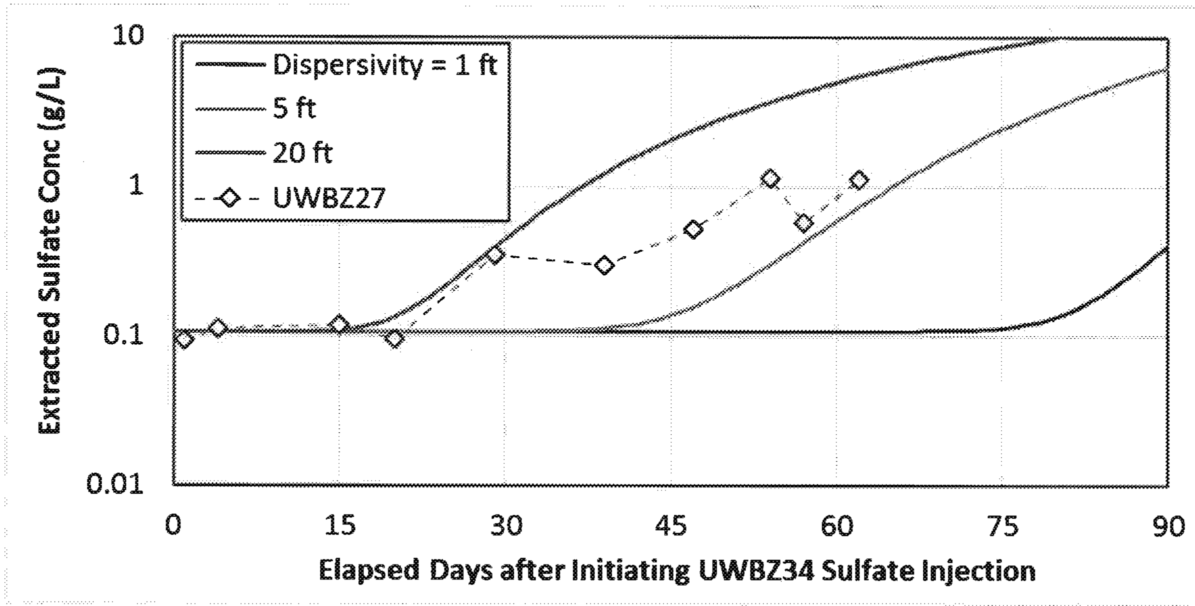
Dispersivity appears to be about 5 ft.

Sulfate Injection in UWBZ34 is largely uncaptured because of low flow in UWBZ27



UWBZ34 Injection

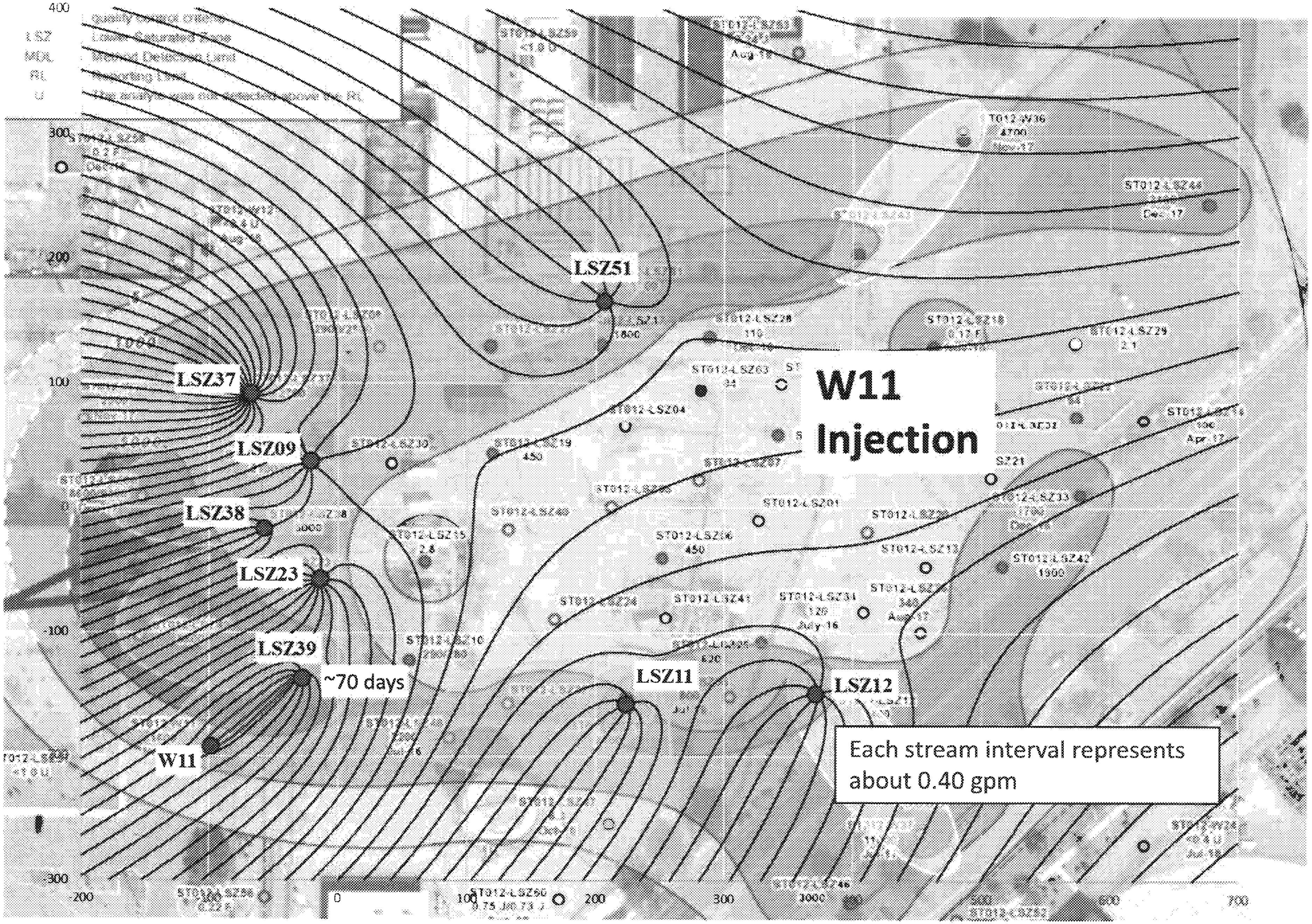
Estimated Extracted Sulfate Concentration in UWBZ27



Sulfate Injection in UWBZ34 Day 0 = 2/28/19

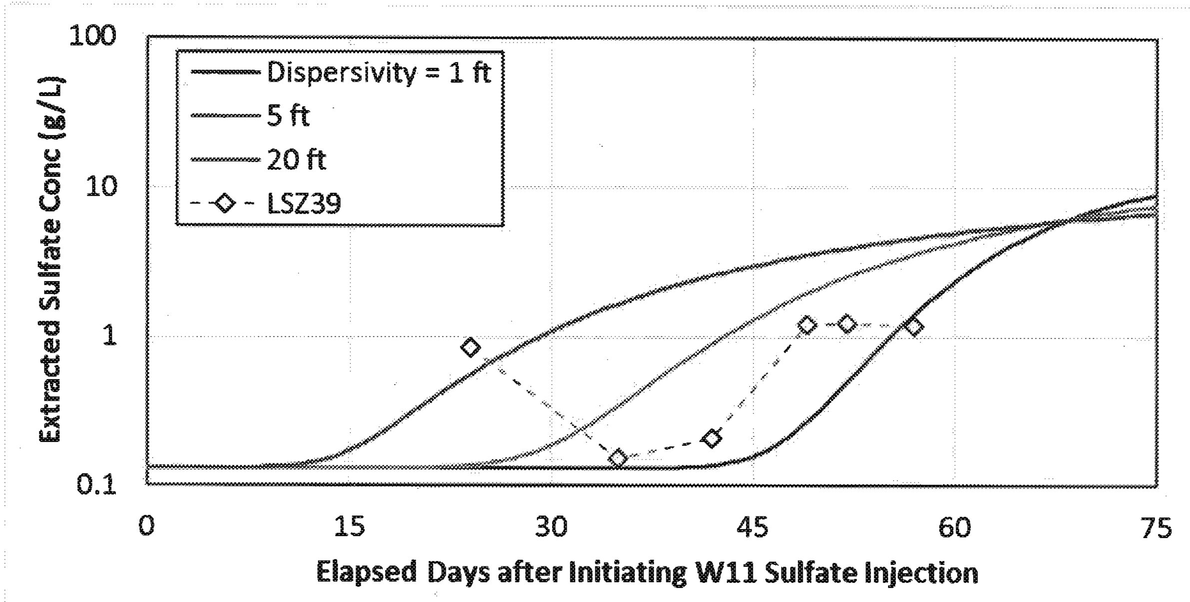
Dispersivity appears to fall between 5 ft and 20 ft.

Sulfate Injection in W11 all heads to LSZ39 under pumping scheme during injection



W11 Injection

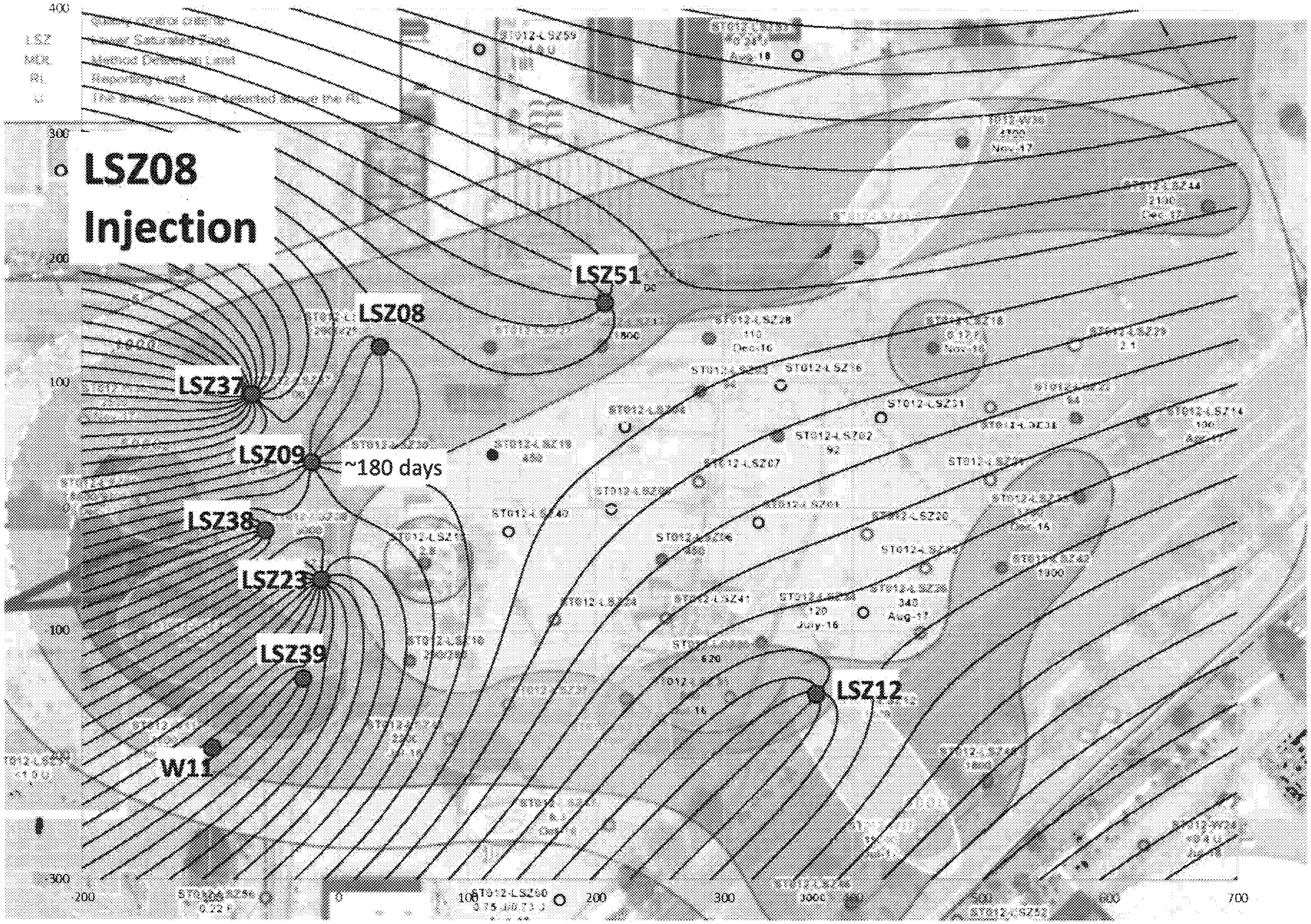
Estimated Extracted Sulfate Concentration in LSZ39



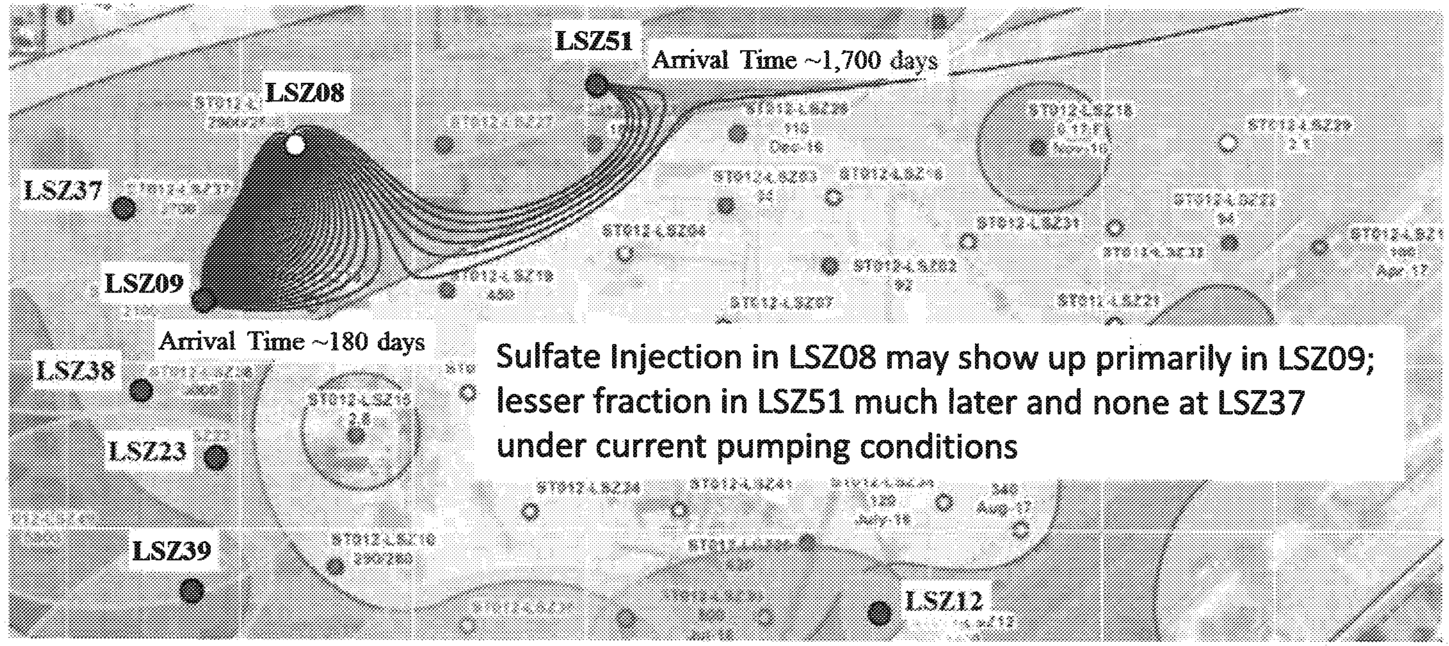
Sulfate Injection in W11 Day 0 = 3/5/19

Dispersivity appears to fall between 5 ft and 1 ft.

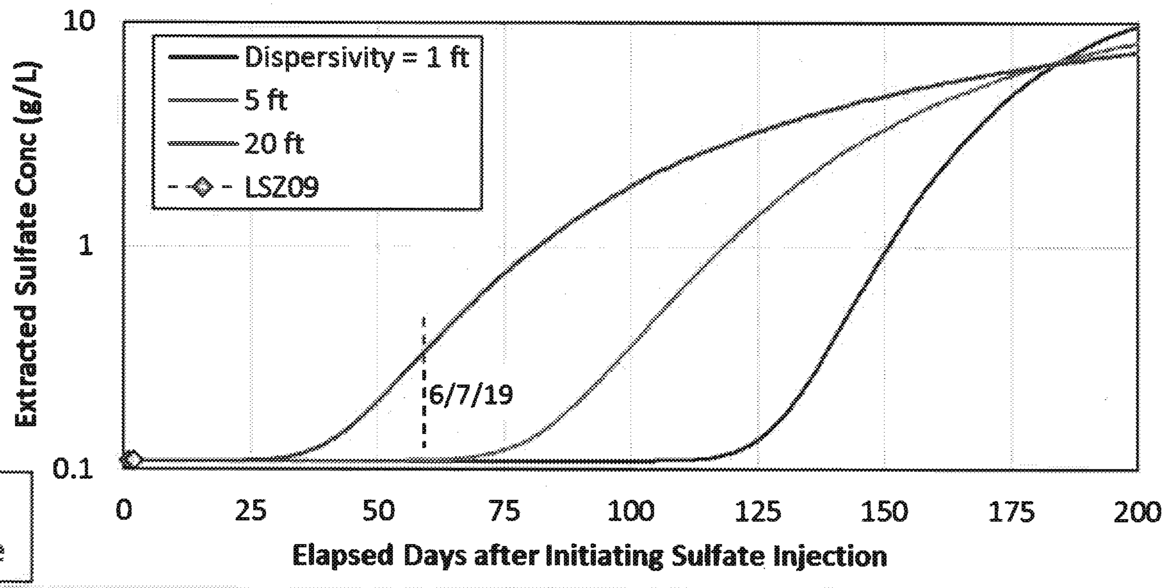
Sulfate Injection in LSZ08 may show up primarily in LSZ09



LSZ08 Injection



Estimated Extracted Sulfate Concentration in LSZ09



Sulfate monitoring should start in LSZ09; none reported to date

Sulfate Injection in LSZ08 Day 0 = 4/9/19